

Radiation Environment Effects on Spacecraft

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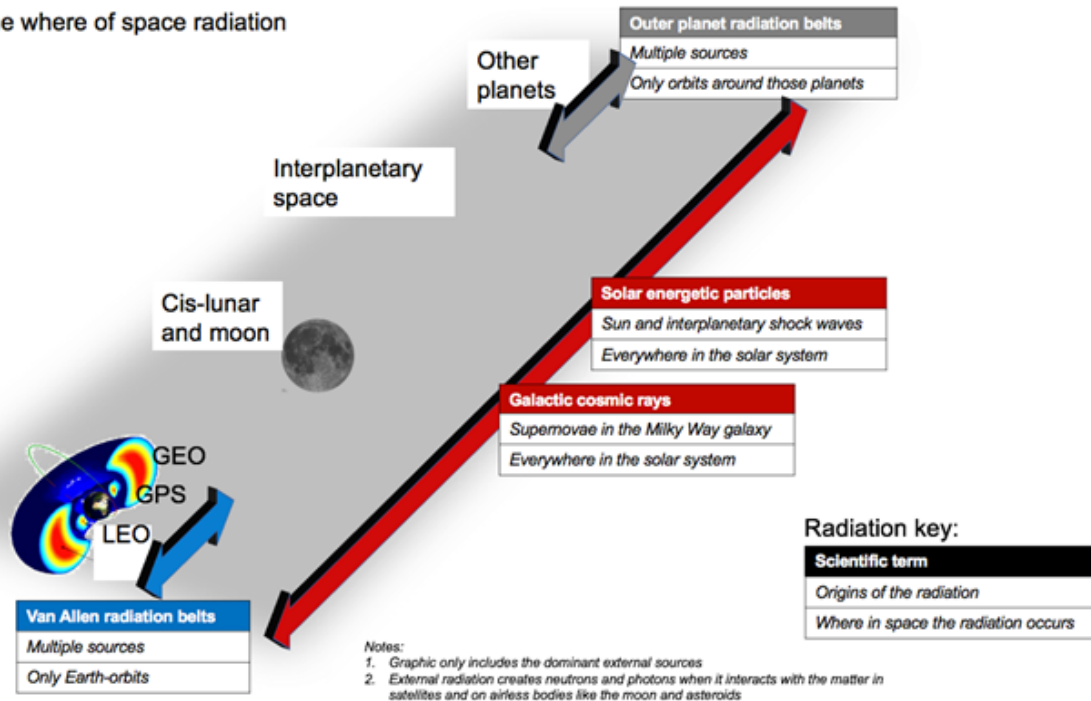
NASA Goddard Space Flight Center

Outline

- Diversity of Space Radiation Environments: Space is not a Place
 - Low Earth, Low Inclination orbits of Earth
 - Polar and Geostationary
 - Interplanetary
 - Other planets and Beyond
- Radiation Threats
 - Degradation Mechanisms
 - Spacecraft Charging
 - Single-Event Effects
- Radiation Hardness Assurance (RHA)
 - Testing
 - Mitigation

Space Is Not A Place: Many Different Space Radiation Environments

Figure: the where of space radiation



• Sources of Radiation

- Galactic Cosmic Rays—present in all space environments; planetary magnetic fields provide shielding in some orbits
- Charged particles trapped by planetary magnetic fields
- Solar Particle Events—sporadic large increases in particle fluxes due to Solar Coronal Mass Ejections, flares, etc.
- Space Plasma environment (including atomic oxygen) important for surface degradation in some orbits

• Radiation Effects

• Cumulative Effects

- Materials/surface degradation, Total Ionizing and Displacement Damage Dose (TID and DDD)
- Prompt effects—Single-Event Effects (SEE), Transient Radiation Effects on Electronics (Sadly, we can't ignore this anymore)

• Relevant environment for any particular radiation effect depends on many factors:

• Position in space

- Proximity to Sun
- Longitude and latitude near planet with magnetic field
- Altitude above a planet (geometric and magnetic shielding)
- Proximity to (cough, cough) manmade sources

• Time

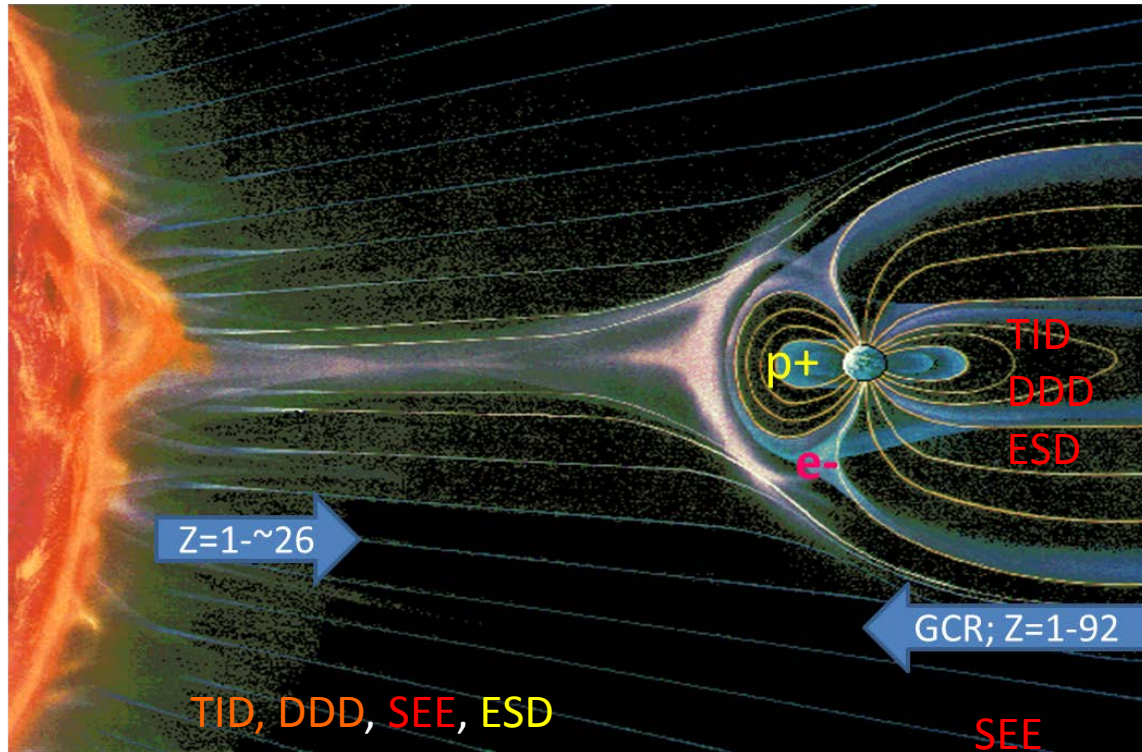
- Solar Maximum vs. Solar Minimum
- Solar Weather, Wind and Events

• Material/Shielding around susceptible element

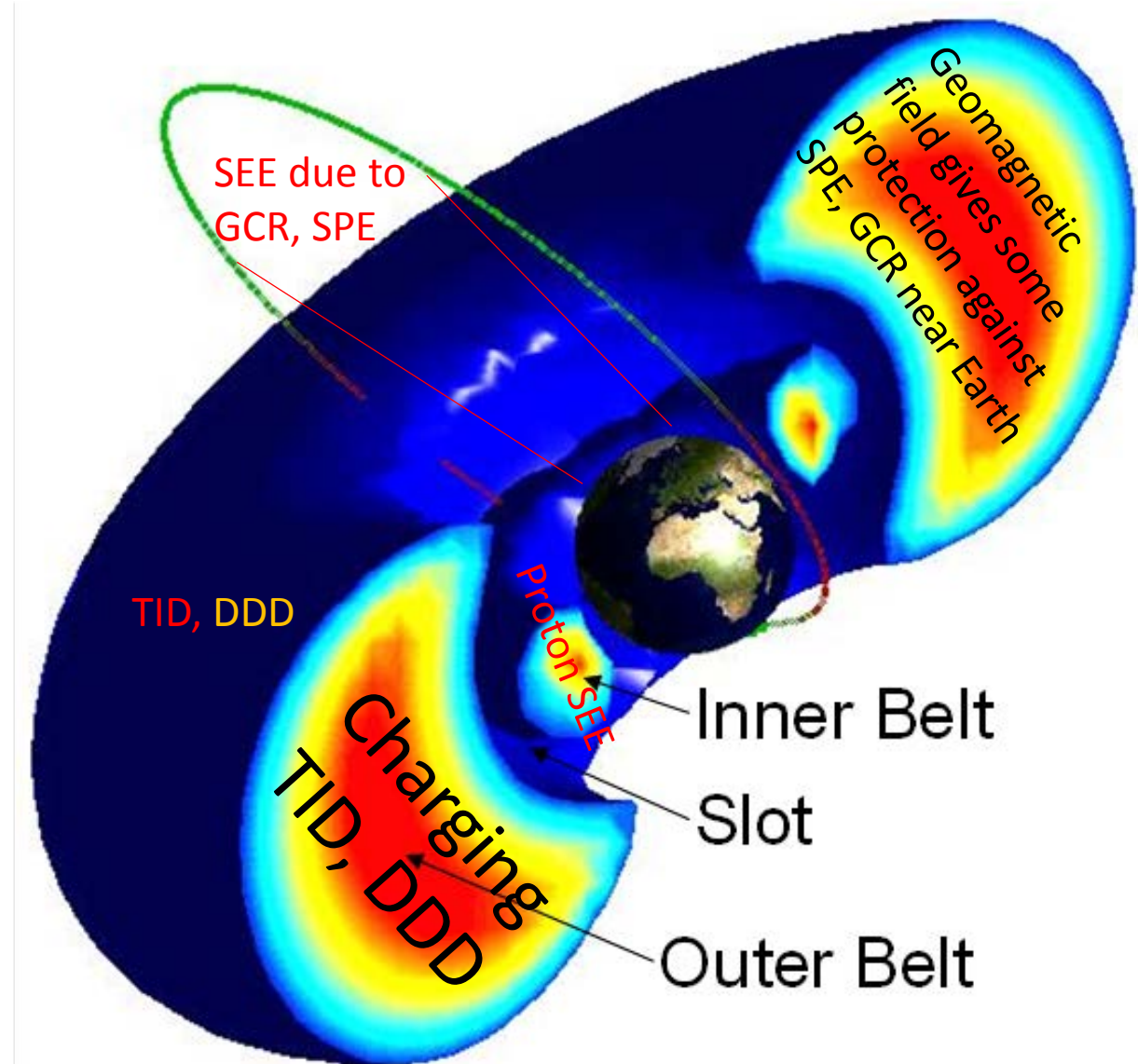
- Material Properties (thermal + electrical conductivity, optical properties,...)

• These many radiation environments tell us: Space is not a place

Where Is Space Radiation And Where Does It Come From?



- Galactic Cosmic Rays (GCR)—VERY high energy, All Z
 - Small flux means main concern is SEE, even hard devices
- Solar Particle Event (SPE)—Moderate energy, Z variable
 - Intermittent high flux—SEE, TID, DDD all concerns
- Trapped radiation belts—mainly protons and electrons
 - High, variable flux; protons—TID, DDD, SEE; e^- —TID, DDD, charging (electrostatic discharge (ESD))



Effects of Space Radiation

Solar Panels

Degraded power from TID/DDD
ESD from surface charging

Guidance and Navigation

Station-keeping/pointing errors from SEE
Star tracker false stars (SEE) and noisy pixels (DDD)

Communications

Bit flips/lost data due to SEE/ESD

Avionics

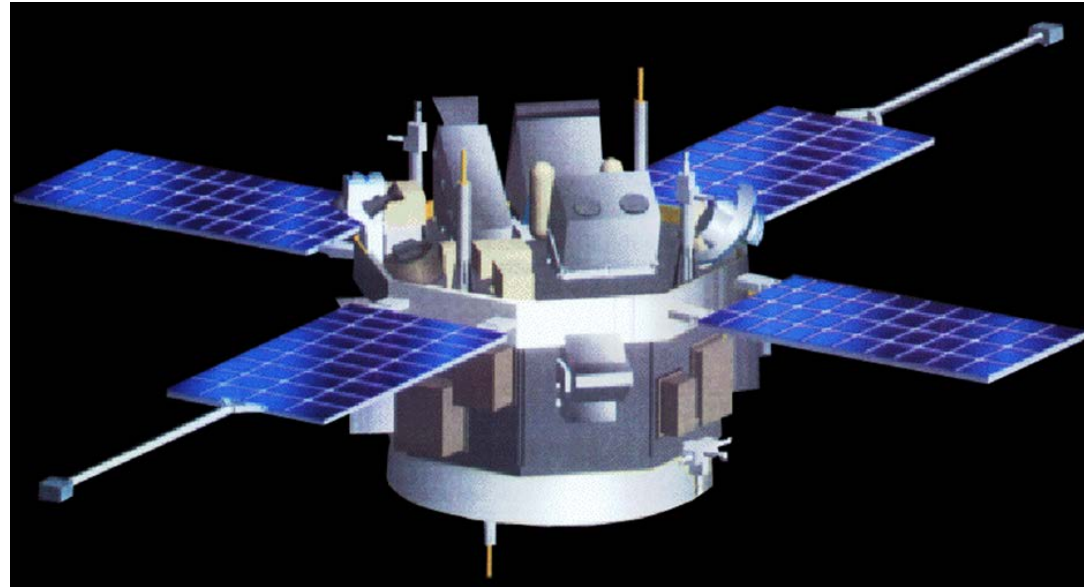
DDD/TID degradation/failure
SEE/ESD malfunction/failure

Power Electronics

DDD/TID degradation/failure
Destructive SEE failure

Contamination

Materials degraded by
TID/DDD, atomic O, charging
contaminate optics, etc.



Thermal from TID/plasma

Darkening of surfaces
Materials degradation

Optics

Darkening of optics from TID
Detector degradation from DDD

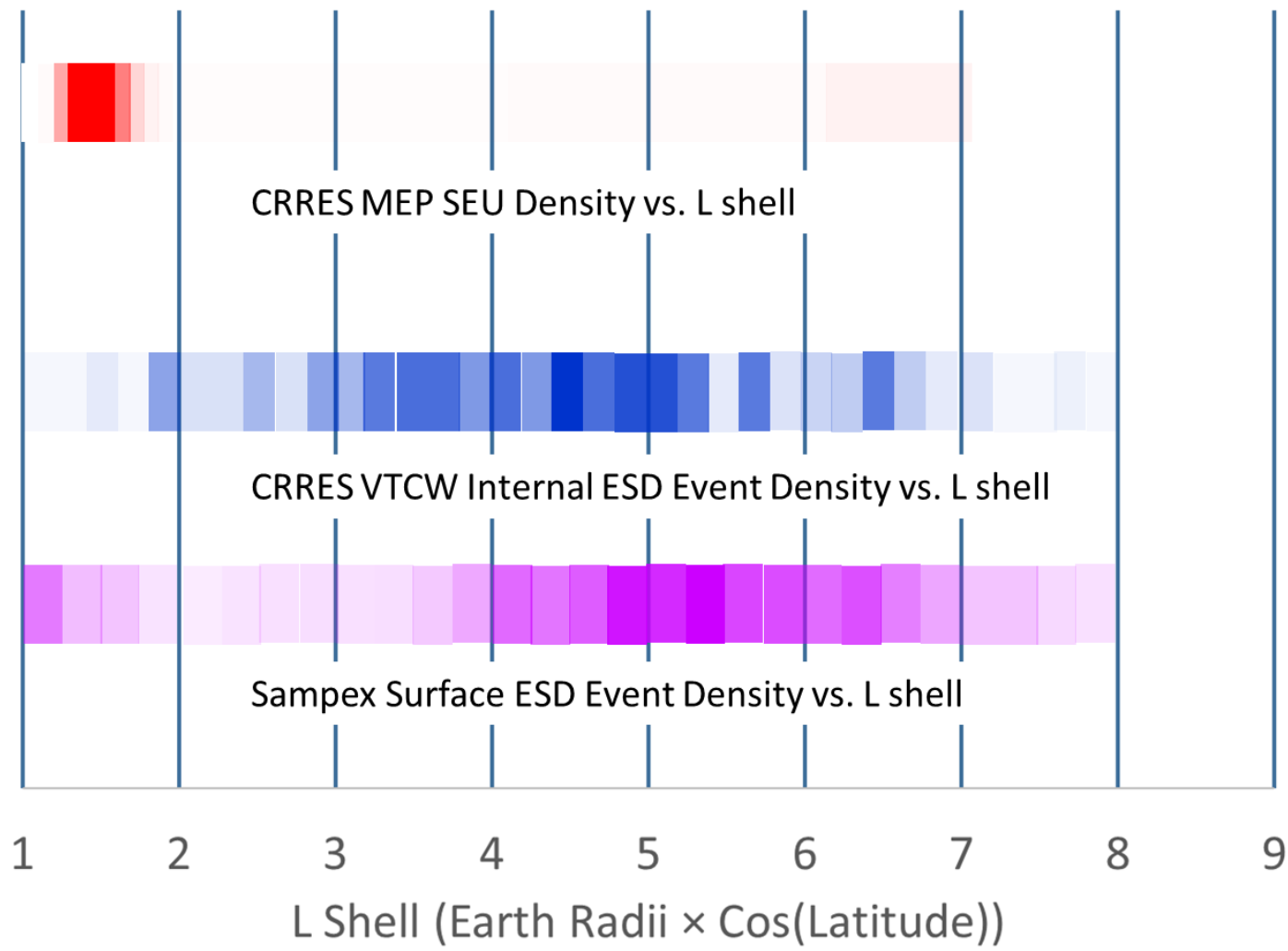
Surface/Materials

Degradation due to plasma,
atomic oxygen, TID, charging

Payload

Loss of data, availability, total loss due to SEE, ESD
Degradation, eventual failure due to TID, DDD

SEE and ESD—Relative Risks and Rates



Attribution of Anomalies	
Diagnosis	Number of Forms
ESD - Internal Charging	74
ESD - Surface Charging	59
ESD - Uncategorized	28
Surface Charging	1
Total ESD & Charging	162
SEU - Cosmic Ray	15
SEU - Solar Particle Event	9
SEU - South Atlantic Anomaly	20
SEU - Uncategorized	41
Total SEU	85
Solar Array - Solar Proton Event	9
Total Radiation Dose	3
Materials Damage	3
South Atlantic Anomaly	1
Total Radiation Damage	16
Micrometeoroid/Debris Impact	10
Solar Proton Event - Uncategorized	9
Magnetic Field Variability	5
Plasma Effects	4
Atomic Oxygen Erosion	1
Atmospheric Drag	1
Sunlight	1
IR background	1
Ionospheric Scintillation	1
Energetic Electrons	1
Other	2
Total Miscellaneous	36

Adapted from *Space Radiation Environment – A Short Course*, NSREC 2016, Paul O’Brien and Joe Mazur
Key: CRRES—Combined Release and Radiation Effects Satellite; MEP—Microelectronics Package Space Experiment;
SEU—Single-Event Upset; VTCW—vehicle time code word

After Koons et al. 6th Spacecraft Charging Technology Conference, 2000

Radiation Effect Characteristics: Single-Event Effects

Characteristics and sources of error determine RHA approach, testing protocols and effective mitigations

- Radiation tests potentially destructive, so must be done on sample representative of flight parts
 - SEE usually vary little part to part or lot to lot
 - Not always true, especially for destructive SEE
- Poisson process
 - Just as likely for first ion as for the last
 - All SEE are independent of all others
 - Process is Poisson per unit ion, not per unit time
- Vulnerability depends on application conditions
 - Voltages, temperature, state of operation...
 - Parts only vulnerable when biased
- Relevant environments include
 - Galactic Cosmic Rays
 - Trapped protons
 - Solar-Event protons and heavy ions
- “Representative”=same process and mask set
- Poisson process implies: even low-rate modes can occur any time in the mission
 - High fluence, high-LET heavy-ion test for worst-case application conditions important to ensure detection
 - Heavy ions are not only far more ionizing than proton recoils, they allow test conditions to be selected—both to encompass worst case and to assess SEE mode dependence
- Mitigation strategies
 - Threat avoidance by using parts not susceptible to SEE modes of concern or avoiding application conditions where susceptibility manifests
 - Redundancy—independence of each SEE means redundancy is an effective mitigation strategy
 - Pay in currency of the realm—bits for bits, function for function (hot spares), system for system
 - Poisson per ion means vulnerability depends on environment
 - For hot spares—primary and redundant unit rates increase with environment; not so for cold spares
 - Cold spares more effective for increased survivability

Radiation Effect Characteristics: Cumulative Effects

- Multiple Cumulative effects: Total Ionizing Dose, Displacement Damage Dose, Atomic Oxygen and energetic plasma exposure
- Consider TID as most complicated mode
 - Cumulative effect—each krad(Si) absorbed make failure more likely with the next krad(Si)
 - Damage accumulates whether parts biased or not
- TID test potentially destructive, so performed on sample representative of flight parts
 - Part-to-part and lot-to-lot variation often significant
- TID susceptibility often application dependent
- Relevant environments include
 - SPE protons and trapped protons and electrons
- DDD shows less part-to-part, lot-to-lot and application dependence
 - Plasma and Atomic O even less
- “Representative” sample= from flight wafer diffusion lot
- Effect is cumulative w/ or w/o bias applied—so threat avoidance is preferred mitigation; redundancy ineffective
 - Avoid susceptible parts or conditions where more susceptible
 - Shielding reduces dose/plasma/particle flux to acceptable limit
 - Design margin reduces probability of susceptibility as long as susceptibility vs. stress distribution is well behaved
- Susceptibility test needs to encompass WC conditions
 - e.g for TID, dose rate, biases, temperature...
- Part-to-part variation means sample size is important
 - Most general method assumes binomial statistics, but requires large sample sizes (230 parts for Ps=99% w/ CL=90%)
 - Assuming failure vs. dose well behaved reduces sample size, but introduces systematic error if distribution pathological

Key: CL—confidence level; Ps—probability of survival; WC—worst case

Radiation Effect Characteristics: Spacecraft Charging (It's complicated)

- Two different modes of charging
 - Surface Charging has 2 contributing mechanisms
 - Photoelectric effect depends on illumination of surfaces and yield positive charging
 - Plasma charging depends on low-energy plasma environment and yields negative charging
 - Internal charging caused by high-energy electrons penetrating dielectrics in spacecraft
 - Both modes also depend on how quickly charge bleeds off of charged surface/dielectric (e.g. resistivity of path to ground)
- Charging neither Poisson, nor cumulative
 - Depends on integral of environment on timescales comparable to discharge time
- Testing is complicated
 - Needs to be performed on representative sample
 - Resistivity depends on sample storage conditions
 - Very difficult to test and model differential charging
- “Representative” means same resistive properties
 - e.g. Same material + outgassing in thermal vacuum
- Mitigation approach is threat avoidance
 - Design rules limit resistivity from metal to ground
 - Operational rules associated with eclipse conditions
 - Shielding can decrease high-energy electron fluxes
 - Environmental monitoring of plasma, electron fluxes
- Redundancy unlikely to be effective
 - Primary redundant systems are in same environment
 - Biased and unbiased systems have same risk
- Testing is difficult
 - Sample resistivities (and therefore integration times) may increase with time as system outgasses
 - System geometries important to reflect differential charging—important for determining charging rate

Which Environments are Important?

- Single-Event Effects caused by protons (trapped and SPE) and heavy ions (GCR and SPE)
 - Average environments determine whether mission meets requirements
 - Average trapped proton environment (AP9@50% confidence or AP8)
 - CREME-96 GCR and Average SPE proton and heavy-ion environments
 - Peak environments important to determine if redundancy overwhelmed by WC environment
 - WC trapped proton environment (South Atlantic Anomaly, AP9@>90% Confidence)
 - SPE proton and GCR environments (e.g. CREME-96 Solar Flare or ESP and PSYCHIC @>90% Confidence)
 - GCR environment does fluctuate, but changes are tiny compared to trapped proton and solar particle event changes.
- Cumulative Effects
 - Except for very short missions (<1-2 years), average environments dominate
 - Solar particle events can dominate TID/DDD for short missions, but few devices susceptible at such doses
 - Other effects (plasma and atomic Oxygen)—need model of average conditions throughout mission
- Charging depends on environments averaged over scales of hours to a day or so
 - Ensuring surfaces grounded, limiting high-resistivity dielectrics limits timescales considered
 - SPE and trapped electron fluctuations (e.g. AE9 at high confidence level over several hours)

Space Radiation Environments Pose a Variety of Threats

- Different threats important for different mission environments
 - Charging important mainly where space plasma and energetic electrons present (GEO, Polar, Jupiter...)
 - Cumulative effects most important where ionizing and energetic particle fluxes are high
 - SEE occur in all environments
- Time scales also vary for different threats
 - Charging takes place over several hours of (usually elevated) environment
 - TID/DDD and other cumulative effects develop and worsen over years
 - Often failure preceded by period of gradual degradation
 - SEE can occur at any time during the mission with equal probability (modula the environment)
- Threat characteristics determine appropriate hardness assurance, testing and mitigation options
 - SEE are Poisson processes
 - Need to be detected if susceptibility present
 - Independent of each other, so appropriate redundancy can be an effective mitigation
 - Cumulative effect failure rates increase w/ dose/time
 - Mitigation means threat avoidance (shielding, part substitution, increased design margin...)
 - Spacecraft charging risk accumulates for all systems when environment is elevated
 - Mitigation means threat avoidance (shielding, low-resistivity path to ground...)
- Knowing what risks apply to your mission is key—where and when change risk calculus